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Respiratory infection risk-based ventilation design method

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ABSTRACT

A new design method is proposed to calculate outdoor air ventilation rates to control respiratory infection risk in indoor spaces. We propose to use this method in future ventilation standards to complement existing ventilation criteria based on the perceived air quality and pollutant removal. The proposed method makes it possible to calculate the required ventilation rate at a given probability of infection and quanta emission rate. Present work used quanta emission rates for SARS-CoV-2 and consequently the method can be applied for other respiratory viruses with available quanta data. The method was applied to case studies representing typical rooms in public buildings. To reduce the probability of infection, the total airflow rate per infectious person revealed to be the most important parameter to reduce the infection risk. Category I ventilation rate prescribed in the EN 16798-1 standard satisfied many but not all type of spaces examined. The required ventilation rates started from about 80 L/s per room. Large variations between the results for the selected case studies made it impossible to provide a simple rule for estimating the required ventilation rates. Consequently, we conclude that to design rooms with a low infection risk the newly developed ventilation design method must be used.

1. Introduction

People around the world suffer multiple airborne respiratory infections each year; this is creating suffering and significant socio-economic costs. COVID-19 has clearly emphasized these issues showing how infections cause not only suffering, but also deaths, massive economic loss and disruption to the functioning of society. Most current buildings do not address airborne infection risks subsequent to a decline in the belief that airborne pathogens are important, perhaps driven by the influential work of Charles V Chapin, who ignored the public health implications of air pollution [1]. The design of ventilation in modern buildings has been limited to thermal comfort and odour (perceived air quality) control. It is suggested that neglecting the infection control could in part be based on perceived risk or the assumption that there are more important ways to control infectious disease, despite ample evidence that healthy indoor environments free of airborne pathogens are essential for public health [2]. This is why a paradigm change is needed recognizing and demanding that buildings are design so that airborne infection control is minimized similarly to what is done for water and ambient air pollution [3].

While individuals can be infected by close contact, the community outbreaks of infection most often occur at a greater distance through the inhalation of airborne virus-laden particles in indoor spaces shared with infected often asymptomatic individuals [4]. Airborne transmission is expected to be potentially dominant mode of transmission in such the case for influenza [5], rhinoviruses [6,7], tuberculosis [8,9], measles [10], Middle East respiratory syndrome coronavirus (MERS-CoV) [11], respiratory syncytial virus (RSV) [12] and, as recently shown, COVID-19 [13–15]. By contrast, the fomites (indirect contact) have been attributed

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Nomenclature

p	probability of infection for susceptibles (−)
N_c	number of disease cases
N_s	the number of susceptible persons in the room
N	total number of persons in the room
I	number of infectious persons
n	quanta inhaled (quanta)
C	time-dependent airborne concentration of infectious quanta (quanta/m^3)
C_{avg}	time-average concentration of infectious quanta (quanta/m^3)
Q_b	volumetric breathing rate of an occupant (m^3/h)
D	duration of the occupancy (h)
η_s	facial mask efficiency for susceptible person (−)
η_i	facial mask efficiency for infected person (−)
η_f	removal efficiency of the room air filter (−)
E	quanta emission rate (quanta/h)
q	quanta emission rate per infected person (quanta/(h pers))
V	volume of the room (m^3)
A	floor area of the room (m^2)
h	room height (m)
λ	first-order loss rate coefficient for quanta/h due to the summed effects of ventilation, deposition onto surfaces, virus decay and possible filtration by portable air cleaner (1/h)
λ_v	outdoor air change rate (1/h)
λ_{dep}	deposition onto surfaces (1/h)
k	virus decay (1/h)
k_f	filtration by portable air cleaner (1/h)
t	time (h)
$t_{1/2}$	half-life of the virus (h)
Q	outdoor air ventilation rate (m^3/h)
Q_f	airflow rate through the filter (m^3/h)
Q_s	supply (outdoor) airflow rate (L/s)
Q_e	extract airflow rate (L/s)
R	event reproduction number (−)
R_0	basic reproduction number (−)

a much smaller role in overall infection transmission [16].

Available information on COVID-19 shows that transmission of this disease has been associated with the close proximity for which general ventilation is not an efficient solution, as well as when ventilation is inadequate especially in crowded spaces. The latter is supported by the evidence from superspreading events where ventilation with outdoor air was measured or estimated to be as low as 1–2 L/s per person [17–19] which is lower by a factor of 5–10 lower than the commonly prescribed 10 L/s per person in existing standards [20,21]. This raises the question on how much ventilation would be needed to considerably reduce airborne transmission of SARS-CoV-2. Also, other factors come into play in that regard such as air distribution and room size.

Before COVID-19, to the best of our knowledge, almost no engineering based measures to limit community respiratory infection transmission were employed in public buildings (excluding health care facilities) or transport infrastructure anywhere in the world, despite the frequency of such infections, and despite the very large health burden and economic losses they caused [22]. The key engineering measure to deal with the airborne transmission is ventilation supported by air filtration and air disinfection [23]. Many organizations provided COVID-19 ventilation guidance including the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) but the guidance how to improve ventilation in existing buildings does not prescribe specific ventilation rates to reduce the risk [24]. Existing indoor climate standards [20,21] use ventilation criteria based on other aspects mainly the control of perceived air quality by the visitors (unadapted) and occupants (adapted persons) that depend on the emissions from humans and building; sometimes the concentration of specific pollutants are used to determine ventilation. In the wake of the current pandemic and considering the loss cost by other infections we need to reconsider the objectives of ventilation to include the removal of airborne pathogens.

The effect of ventilation with outdoor air on the virus concentration in a room is illustrated in Fig. 1. In the case of fully mixing ventilation, the concentration of pollutants is supposed to be equal in every point in a room. However, the concentration is higher in close proximity of the source. Fully mixed concentration builds up when the distance between an infected person and another person is about 1.5 m for typical cases under interest such as speaking or coughing person [25]. Therefore, general ventilation should be applied together with physical distancing, and proximity of less than 1.5 m would necessitate either personal protection or personal ventilation solutions.

If the mixing is not perfect, or other air distribution methods are used

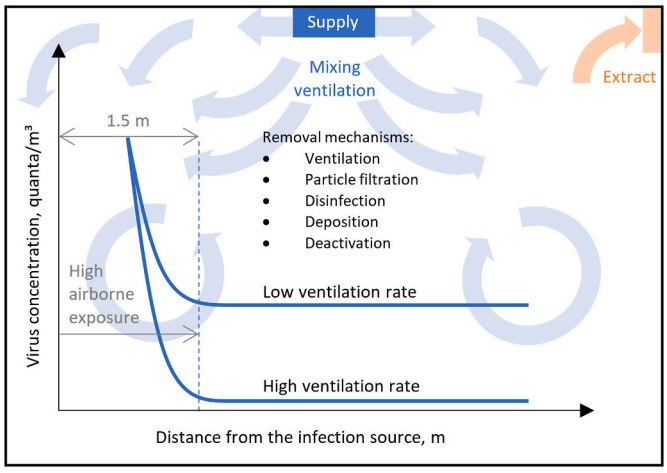


Fig. 1. Illustration of how a viral load of an infectious person leads to aerosol concentration in a room. At about 1.5 m distance from the source the virus concentration has decreased to a constant level depending on the emission rate and removal mechanisms.

intentionally to create low-concentration zones, spatial concentration differences in a room can be significant. These can be taken into account by dilution ratio or ventilation effectiveness as described in Refs. [26,27]. Ventilation effectiveness of advanced air distribution systems has been reviewed in Ref. [28]. Room conditioning units with recirculation and filtration affect contaminant distribution in room by changing airflow field and by filtration removal, which effects may be estimated with linear expression derived in Ref. [29].

Defining the acceptable infection risk level needs a specific effort because infection risk-based ventilation design has so far not been used in public indoor spaces. In principle, the risk assessment can be conducted in community, building, room, personal or even in the breathing zone level [30]. Very low risk levels may lead to solutions which are not feasible, as a building should be designed and operated according to its purpose and the activities conducted there. To maintain airborne infection risk below an acceptable level refers to individual risk of infection calculation for each susceptible occupant. The acceptable value of the individual risk may be estimated from event reproduction number (the expected number of new infections arising from a single

infectious occupant at an event) as the management of the event reproduction number is important for the control of an epidemic especially for indoor spaces with a high number of people [3]. If it is not possible to increase ventilation to the point of reducing the risk to an acceptable level then air-cleaning measures may be applied to enforce the removal effect.

In this study we applied existing knowledge to derive an additional, infection probability-based ventilation criterion. For this purpose, ventilation rates must be risk-based rather than absolute, which means they need to be developed based on the assessment of the infection risk, considering the pathogen emission rates and the infectious quantum (the dose of infectious airborne pathogens required to cause infection in 63% of susceptible persons). Infectious quanta are not known for all respiratory diseases, particularly not the new ones, but there is some data that can be applied. Furthermore, the effect of assumption of a steady state is evaluated and, a new simplified steady state ventilation equation is derived which enables us to calculate the ventilation rate for given probability of infection and quanta emission rate values and is suitable for application in standards in parallel with existing ventilation criteria. Acceptable risk level is calculated from event reproduction number. This newly developed equation can be applied to design rooms with low infection risk that in some cases can be feasible, but in some cases not, as demonstrated by a number of case studies conducted in public buildings. Compared to existing REHVA COVID-19 ventilation calculator [31], developed method uses the same Wells-Riley model but derives a new equation enabling to calculate explicit ventilation rates for acceptable risk levels which are calculated from the event reproduction number as another novelty. The study is limited to general ventilation with fully mixing air distribution and effects on spatial concentration differences at different locations in the rooms are not analysed.

2. Modelling airborne infection risk

To set up an infection risk based general ventilation criterion, we apply the Wells-Riley model with quanta emission rates calibrated for SARS-CoV-2. The probability of infection is estimated in common public rooms with ventilation according to the EN 16798-1 standard Category I to III ventilation rates.

Infection risk can be calculated for different activities and rooms using a standard airborne disease transmission Wells-Riley model calibrated to COVID-19 with the correct source strength (quanta emission rates). In this model, the viral load emitted is expressed in terms of the quantum emission rate (E, quanta/h). A quantum is defined as the dose of airborne droplet nuclei required to cause infection in 63% of susceptible persons. The model of infection risk due to aerosol transmission is based on the Wells-Riley formulation [32,33] as amended by Gammaitoni and Nucci [34]. With the Wells-Riley model [35], the probability of infection (p) is related to the number of quanta inhaled (n) according to equation (1):

$$p = \frac{N_c}{N_s} = 1 - e^{-n} \tag{1}$$

where.

p the probability of infection for susceptible persons (−)
N_c the number of disease cases
N_s the number of susceptible persons in the room
n quanta inhaled (quanta).

Number of susceptible persons makes no differentiation of high-risk vs. low-risk populations but it is possible to apply stringent probability levels for high-risk groups. To include vaccinated persons, the number of susceptible persons can be reduced assuming 100% efficiency of vaccination. If it is assumed that there are no vaccinated persons in the room the number of susceptible persons becomes $N_s = N - I$ where N is the total number of persons in the room and I is the number of infectious persons.

The quanta inhaled (n, quanta) depends on the time-average quanta concentration (C_{avg}, quanta/m^3), the volumetric breathing rate of an occupant (Q_b, m^3/h) and the duration of the occupancy (D, h):

$$n = C_{avg} Q_b \mathrm{D} \tag{2}$$

In Equation (2) it is assumed that the breathing rate is a fixed value and in the calculation of the time-average quanta concentration also a fixed quanta emission rate is used. These fixed values describe average values of the event, however in reality somebody can cough or not cough with the same breathing rate and create variation in the emissions. It is hence assumed that the emission rate comes only from breathing or speaking and the concentration in exhaled air is independent of breathing rate and other respiratory activities. If a person is wearing a mask, the facial mask efficiency η_s for a susceptible person reduces the quanta inhaled:

$$n = C_{avg} Q_b (1 - \eta_s) \mathrm{D} \tag{3}$$

The airborne quanta concentration increases with time from an initial value of zero following a "one minus exponential" form, which is the standard dynamic response of a fully mixed indoor volume to a constant source. A single zone fully mixed material balance model for the room is applied to calculate the concentration:

$$\frac{dC}{dt} = \frac{E}{V} - \lambda C \tag{4}$$

where.

E quanta emission rate (quanta/h)
Vvolume of the room (m^3)
λfirst-order loss rate coefficient [36] for quanta/h due to the summed effects of ventilation (λ_v, 1/h), deposition onto surfaces (λ_{dep}, 1/h) and virus decay (k, 1/h) and filtration by a portable air cleaner if applied (k_f, 1/h), $\lambda = \lambda_v + \lambda_{dep} + k + k_f$
C time-dependent airborne concentration of infectious quanta (quanta/m^3).

A fully mixed material balance model is not capable to account spatial concentration variances in the room and may lead to some uncertainties as discussed in Section 7. Ventilation in the loss rate coefficient means all virus free air supplied to the room including outdoor air ventilation, infiltration, virus free air from recirculation and transfer air from other rooms. In the single zone model used in this study it is not possible to take into account recirculation for which multi-zone modeling would be needed and in the public rooms with human occupancy under interest, ventilation is typically in balance or supply airflow rate is larger than extract airflow rate, i.e. there is no transfer air to the room. Therefore, in the following, ventilation is treated as an outdoor air ventilation. The quantum emission rate is generated by I infected persons and while accounting for facial mask efficiency, the emission rate can be described as:

$$E = (1 - \eta_i) I q \tag{5}$$

where.

I the number of infectious persons
q quanta emission rate per infected person (quanta/(h pers))
η_i facial mask efficiency for infected person, 0 for no mask (−).

The efficiency of a facial mask worn by an infectious person might differ from the efficiency of a mask worn by a susceptible occupant even if they wear nominally identical masks, because the emitted droplets are larger and contain more water than inhaled, shrank droplets. For instance, a worst-case mask efficiency values of 0.5 for an infected person and 0.3 for a susceptible person have been measured by Ueki et al. [37].

A surfaces deposition loss rate could vary 0.24-1.5 1/h depending on particle size range. Coleman et al. [40] report that fine aerosols (≤5 μm) constituted 85% of the viral load that supports the use of the lower deposition loss value. Aganovic et al. [51] has analyzed relative humidity effects on the deposition and decay, allowing to treat these loss rates as a fixed values for common indoor conditions. In this study we used a deposition loss rate of 0.3 1/h that was estimated based on data from Thatcher et al. and Diapouli et al. [38,39].

For virus decay in the case of no sunlight, Fears et al. [41] reported no decay in virus-containing aerosol for 16 h at 53% relative humidity, whereas van Doremalen et al. [42] estimated the half-life of airborne SARS-CoV-2 as 1.1 h, which equates to a decay rate $k = \ln(2)/t_{1/2}$ of 0.63 1/h. An average value of these two studies is 0.32 1/h, which is used in our calculations.

For a portable air cleaner, the filtration removal rate (k_f) depends on the rate of airflow through the filter (Q_f), and the removal efficiency of the filter (η_f), V being a room volume:

$$k_f = \frac{Q_f \eta_f}{V} \tag{6}$$

For portable cleaners with a high-efficiency particle air (HEPA) filter, the clean air delivery rate (CADR, m^3/h) is provided and the filtration removal rate can be calculated as $k_f = CADR/V$. It should be noted that the removal efficiency of filters and the CADR are particle-size dependent. These parameters are to be estimated based on the size distribution of virus-containing particles. The following calculation examples provided in the following are conducted without air cleaners.

Assuming the quanta concentration is 0 at the beginning of the occupancy, equation (3) is solved and the average concentration determined as follows:

$$C(t) = \frac{E}{\lambda V}\left(1 - e^{-\lambda t}\right) \tag{7}$$

$$C_{avg} = \frac{1}{D}\int_0^D C(t)dt = \frac{E}{\lambda V}\left[1 - \frac{1}{\lambda D}\left(1 - e^{-\lambda D}\right)\right] \tag{8}$$

where.

t time (h).

If steady state is assumed, equations (7) and (8) will simplify so that terms in round and square brackets are equal to one. Calculation examples with these equations can be found in studies analysing the Skagit Valley Chorale event [18] and quanta emission rates for SARS-CoV-2 [43]. It is reported in Buonanno et al. [44] that quanta emission rates vary over a large range of 3–270 quanta/h depending strongly on the activity; higher values apply for loud speaking, shouting and singing and also for higher metabolism rates (Table 1). In reality, quanta emissions have probability distributions, but in exposure scenarios with constant parameters (ventilation, occupancy, activity, emission) a fixed values, more specifically 66th percentile values, can be used according to Buonanno et al. [44]. In Table 1, conservative values of 90th percentile are used because of high uncertainty in quanta values. The use of fixed quanta values is justified, because the focus of this paper is on the steady state ventilation airflow rate sizing at design (constant) occupancy and emission conditions. Quanta values in Table 1 can be compared with available quanta emission rate data for some other diseases, such as for 1–10 quanta/h for the common cold/rhinovirus [45], and 0.1–0.2 quanta/h on average, but 630 quanta/h max daily rate for Influenza [46]. Hence, they show that SARS-CoV-2 quanta values for resting and not speaking are of the same order of magnitude. Volumetric breathing rates depend on the activity being undertaken as shown in Table 2.

In the present analyses, the time-average quanta/h values calculated from activities shown in Table 1 are used: 5 quanta/h for office work and classroom occupancy (5% of the time assumed for speaking), 15 quanta/h for a restaurant (30% of the time speaking), 21 quanta/h for sports and 19 quanta/h for meeting rooms (40% of the time speaking). Therefore, the classroom cases apply for one infectious student – the infectious teacher cases with longer speaking time are not considered.

3. A new design method

While equations (1), (2) and (7) allow us to calculate the probability of infection for any room where full mixing is assumed, these equations do not allow us to determine the ventilation rate needed for a given probability of infection. The ventilation rate can be solved iteratively by selecting an initial value and calculating probability and then changing ventilation rate to smaller or larger to get the intended probability value. With a steady state assumption, it is possible to derive an equation that can be directly used for ventilation sizing. Substituting equation (3) will rewrite equation (1) as follows:

$$p = 1 - e^{-C_{avg} Q_b (1-\eta_s) \mathrm{D}} \tag{9}$$

Assuming steady state and substituting C_{avg} from equation (8) and E from (5), and considering that outdoor air ventilation rate $Q = \lambda_v V$ results in the following equation:

$$p = 1 - e^{-\frac{(1-\eta_i) I q Q_b (1-\eta_s) \mathrm{D}}{Q + \left(\lambda_{dep} + k + k_f\right) V}} \tag{10}$$

Solving equation (10) for outdoor air ventilation rate Q (m^3/h) gives:

$$Q = \frac{(1-\eta_i) I q Q_b (1-\eta_s) \mathrm{D}}{\ln\left(\frac{1}{1-p}\right)} - \left(\lambda_{dep} + k + k_f\right) V \tag{11}$$

Thus in the case when no masks are used, no air cleaner is installed and there is one infected person, equation (11) simplifies as follows:

$$Q = \frac{q Q_b \mathrm{D}}{\ln\left(\frac{1}{1-p}\right)} - \left(\lambda_{dep} + k\right) V \tag{12}$$

Equation (11) allows us to calculate the required outdoor ventilation rate per infected person(s) for a given probability of infection and quanta emission rate. It shows that a low probability leads to a high ventilation rate and that the room volume also has a positive effect. The ventilation rate may become zero or even negative if other removal mechanisms (in the right part of the equation) are sufficiently high to remove the virus.

There are many possible considerations as to how the target acceptable probability of infection level can be selected. In the present analyses, we used the levels of 5%, 3% and 1% individual probabilities as examples to compare the effect of ventilation rates prescribed in the existing standards. More meaningful approach to define an acceptable

Table 1
90th percentile SARS-CoV-2 quanta emission rates for different activities [44].

Activity	Quanta emission rate q, quanta/(h pers)
Resting, oral breathing	3.1
Heavy activity, oral breathing	21
Light activity, speaking	42
Light activity, singing (or loudly speaking)	270

Table 2
Volumetric breathing rates [47,48].

Activity	Breathing rate Q_b, m^3/h
Standing (office, classroom)	0.54
Talking (meeting room, restaurant)	1.1
Light exercise (shopping)	1.38
Heavy exercise (sports)	3.3

probability level for a specific room is to use an event reproduction number R as recommended in Refs. [3,30]. R is defined as number of new disease cases divided by number of infectors. Considering that the number of new cases $N_c = p\,N_s$ an acceptable individual probability for a specific room can be calculated:

$$p = \frac{RI}{N_s} \tag{13}$$

To keep the basic reproduction number $R_0 < 1$ of COVID-19 due to airborne transmission, indicating the disease spreading in population, $R < R_0$ because susceptible persons may be exposed to more than one event [30]. In the present analyses $R = 0.5$ was used. With this R value, at a very low number of persons, equation (13) provides high individual probabilities ($p = 0.5$ for 2 persons and $p = 0.125$ for 5 persons) and the maximum acceptable individual probability was limited to 0.1 (corresponds to $N = 6$).

To illustrate the difference between the use of fixed p value and p value calculated with Equation (13), an example for one case study in a room is shown in Fig. 2 indicating that the smaller rooms with a lower number of persons may show higher individual probabilities; however, the number of infected persons can still be higher in larger rooms with lower individual probability but a higher number of persons. This example is calculated for the case with the large meeting room of 52.5 m^2 described in Table 3, in which the floor area and the number of persons are changed with a fixed occupant density (2.19 m^2 per person) from 2 to 50 persons corresponding to a floor area of 4.4–109 m^2. In Fig. 2, the number of new disease cases in the room are reported. The number of persons starts from one, because in the case of one infectious person in the room the probability of infection is zero because there are no susceptible persons in the room. The highest probability value is achieved in a small room of 4.4 m^2 with two persons representing a case with one infectious and one susceptible person. Results with Category II ventilation rate of 3.9 L/s m^2 show that high individual probabilities in the case of a small number of persons have led to less than one infection, but in the case of 20 and more persons, much lower individual probabilities have led to more than one infection because of the high number of susceptible persons. This tendency will apply also at other occupant density values.

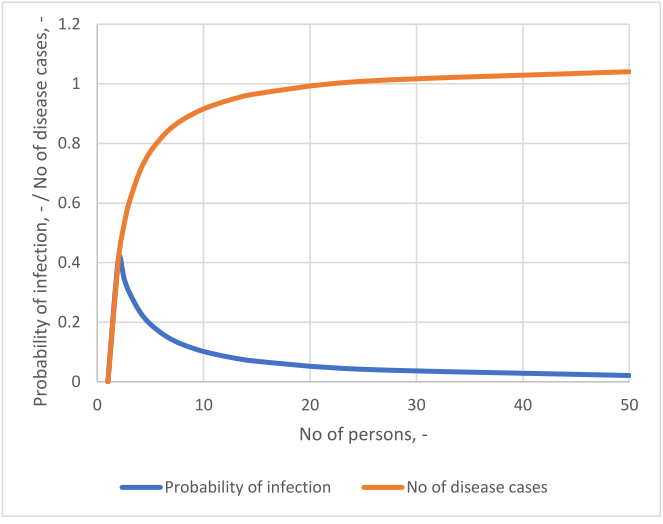


Fig. 2. Illustration of the dependency of probability and the number of new disease cases calculated with fixed occupant density of 2.19 m^2 per person and ventilation rate 3.9 L/s m^2 so that the number of occupants and floor area is varied. Two persons in the figure correspond a floor area of 4.4 m^2 and 50 persons to 109 m^2.

4. Case studies

Case studies on real room layouts and ventilation systems were conducted to test proposed ventilation criteria based on infection risk. These case studies are described in Table 3 and include Estonian office, school and university buildings where recirculation is not used in the ventilation systems with mechanical supply and exhaust and heat recovery. Ventilation rates therefore represent only outdoor air rates; room air cleaners were not used in these buildings. In some rooms, supply and extract ventilation rates are not in the balance so that supply airflow rates are higher than that extract airflow rates. This means that a part of supply air is transferred to other rooms where it is extracted; on a building level, the total supply and extract air flow rates are kept in balance. Three individual infection probability levels of 5%, 3%, 1%, and alternatively the event reproduction number $R = 0.5$ were applied to determine the required outdoor ventilation rates. For some selected rooms, the required ventilation rates were also calculated with the masks.

Ventilation rates, based on Category II of the EN 16798–1:2019 standard, were applied for all the rooms, but for an open plan office and classroom, Category III ventilation rates were applied to see how the lower ventilation rates potentially highlight the effect of the steady state assumption. Ventilation rates in L/s units (1 L/s = 3.6 m^3/h) were calculated from L/s per person and low polluting building materials L/s per floor area components as follows:

- 10 L/s per person + 1 L/s per floor area in Category I;
- 7 L/s per person + 0.7 L/s per floor area in Category II;
- 4 L/s per person + 0.4 L/s per floor area in Category III.

The probability of infection was calculated with dynamic concentration build up and steady state approximation to analyse the applicability of the steady state approximation in the proposed ventilation criterion equation.

5. Probability of infection in case study rooms

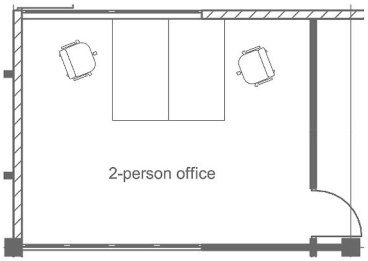
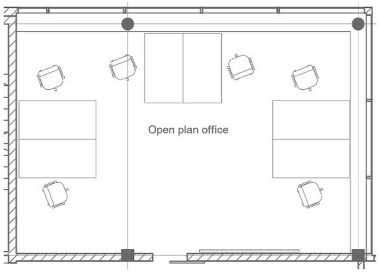
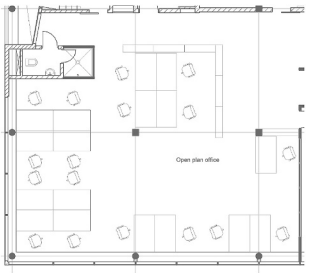
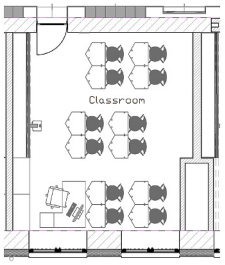
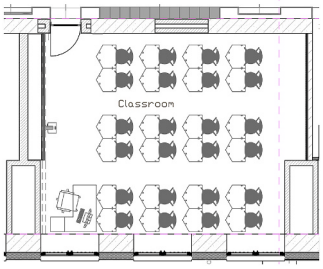
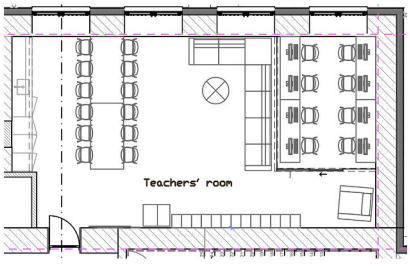
Equation (2) illustrates that reduction of the virus concentration with outdoor ventilation would control the exposure, i.e., the dose depending on the breathing rate, concentration and time. There are two major ways to reduce the dose and infection risk: to increase the ventilation and to reduce the occupancy time (if air filtration or disinfection are not considered). The following infection risk estimates have been calculated allowing us to compare the effect of ventilation and room parameters. It is assumed that there is one infectious person in all calculated rooms. This is justified by the typical COVID-19 infection rates in the general population, which have of a magnitude of 1:100 or 1:1000; therefore, the assumption that only one infected person is in a room that is occupied by, e.g., 10 (office), 25 (school) or 100 (restaurant) persons is reasonable. Results for the rooms with Category II ventilation rates are shown in Table 4.

Calculation with the concentration dynamic build-up and steady state concentration is shown in Fig. 3 and Fig. 4. The results show that in large, well-ventilated rooms the individual probability of infection is lower that is visible in classrooms, open plan offices and in a large meeting room. The Category III ventilation rate of 0.8 L/s m^2 in an open plan office led to significantly higher probability. The 2-person office shows the highest probability, because even if well ventilated, the airflow per infected person is much smaller than that in large rooms. High quanta generation during speaking and physical exercises is evident in meeting rooms and sport facilities.

High total ventilation rates per infected person (assuming one infectious person) explain low probabilities in larger rooms. The number of occupants affects ventilation sizing but is not included in the infection probability equations because the calculation are made per number of infected persons. The room height (volume) matters in terms of the

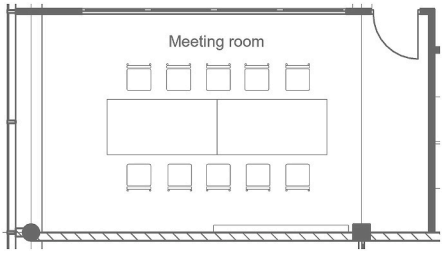
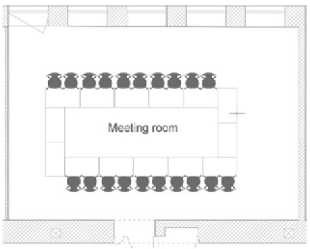
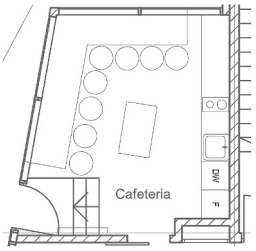
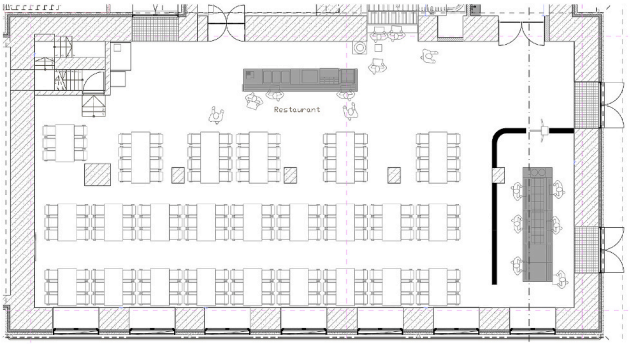
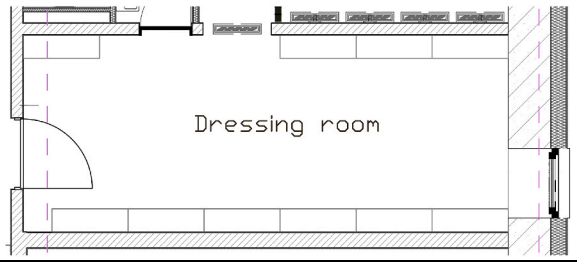
Table 3

Description of case studies used for the ventilation criterion equation testing. Q_s *= supply air flow rate and* Q_e *= extract air flow rate from ventilation drawings are informative and are not used in the analyses, where the reference was Category II ventilation rate.*

Room data	Room layout
2-person office $A = 21.0$ m^2 $h = 2.6$ m $V = 54.6$ m^3 $Q_s = 30$ L/s $Q_e = 30$ L/s $N = 2$ pers $D = 8$ h $Q_b = 0.57$ m^3/h $q = 5$ quanta/h	
Open plan office $A = 56.7$ m^2 $h = 2.6$ m $V = 147.4$ m^3 $Q_s = 80$ L/s $Q_e = 60$ L/s $N = 6$ pers $D = 8$ h $Q_b = 0.57$ m^3/h $q = 5$ quanta/h	
Open plan office $A = 173.2$ m^2 $h = 2.6$ m $V = 450.3$ m^3 $Q_s = 165$ L/s $Q_e = 140$ L/s $N = 17$ pers $D = 8$ h $Q_b = 0.57$ m^3/h $q = 5$ quanta/h	
Classroom $A = 31.6$ m^2 $h = 3.5$ m $V = 110.9$ m^3 $Q_s = 120$ L/s $Q_e = 120$ L/s $N = 13$ pers $D = 6$ h $Q_b = 0.57$ m^3/h $q = 5$ quanta/h	
Classroom $A = 47.8$ m^2 $h = 3.5$ m $V = 167.8$ m^3 $Q_s = 200$ L/s $Q_e = 200$ L/s $N = 25$ pers $D = 6$ h $Q_b = 0.57$ m^3/h $q = 5$ quanta/h	
Teachers' room $A = 62.4$ m^2 $h = 3.5$ m $V = 220.9$ m^3 $Q_s = 94$ L/s $Q_e = 94$ L/s $N = 20$ pers $D = 4$ h $Q_b = 0.57$ m^3/h $q = 19$ quanta/h	
Meeting room $A = 29.6$ m^2 $h = 2.6$ m $V = 77.0$ m^3	

(*continued on next page*)

Table 3 (*continued*)

Room data	Room layout
$Q_s = 55$ L/s $Q_e = 25$ L/s $N = 10$ pers $D = 2$ h $Q_b = 0.76$ m^3/h $q = 19$ quanta/h	
Meeting room $A = 52.5$ m^2 $h = 3.2$ m $V = 168.0$ m^3 $Q_s = 200$ L/s $Q_e = 180$ L/s $N = 24$ pers $D = 2$ h $Q_b = 0.76$ m^3/h $q = 19$ quanta/h	
Cafeteria $A = 18.3$ m^2 $h = 2.6$ m $V = 47.6$ m^3 $Q_s = 60$ L/s $Q_e = 35$ L/s $N = 8$ pers $D = 0.5$ h $Q_b = 0.71$ m^3/h $q = 15$ quanta/h	
Restaurant $A = 259.5$ m^2 $h = 2.9$ m $V = 739.6$ m^3 $Q_s = 960$ L/s $Q_e = 770$ L/s $N = 154$ pers $D = 1$ h $Q_b = 0.71$ m^3/h $q = 15$ quanta/h	
Dressing room $A = 18.3$ m^2 $h = 2.9$ m $V = 52.2$ m^3 $Q_s = 128$ L/s $Q_e = 0$ L/s $N = 25$ pers $D = 0.25$ h $Q_b = 0.76$ m^3/h $q = 19$ quanta/h	

concentration development, so that the source E is switched on at time $t = 0$ and the concentration starts to build up. The use of the steady state concentration instead of average concentration calculated with a dynamic build-up caused a difference during the first hour. This steady state overestimation is reasonably small and may also be described as a horizontal shift of the probability curve that is shorter than 30 min (the only exception is an open plan office with Category III ventilation that shows a shift of about 35 min). In rooms with higher ventilation rates, the steady state overestimation is barely visible.

6. Application of the design method in case study rooms

The ventilation rate equation (12) has been applied to the case studies described in Table 3 (see results in Fig. 5 a). Ventilation rates needed for the individual probability of infection of 5%, 3% and 1% were calculated for these rooms and compared with the present ventilation rates. The original ventilation rates in the case study rooms were close to Category II values (as defined in EN 16798–1), and for comparison Category II and I ventilation rates are shown in figures. The results show that lower individual probability levels of 3% and 1% are more easily achievable in larger rooms; in the large classroom a Category II ventilation rate is enough for 3%.

The respiratory infection-based ventilation rate calculation was repeated by applying facial masks for both infected (mask efficiency 0.5) and susceptible persons (mask efficiency 0.3). The results in Fig. 5 b) show that Category II ventilation rate achieves a 1% probability level in

Table 4
Probability of infection calculation in the case study rooms with Category II ventilation rates and concentration dynamic build-up.

	No of persons	Occu-pancy time	Ventilation rate per floor area	Quanta emission rate	Breathing rate	Air change rate	Total first order loss rate	Probability of infection
	pers	h	L/(s m^2)	quanta/h	m^3/h	λ_v (h^{-1})	λ (h^{-1})	–
2-person office 21 m^2	2	8	1.37	5	0.57	1.90	2.52	0.145
Open plan office 57 m^2	6	8	1.44	5	0.57	1.99	2.61	0.055
Open plan office 173 m^2	17	8	1.39	5	0.57	1.92	2.54	0.019
Classroom 32 m^2	13	6	3.58	5	0.57	3.68	4.30	0.034
Classroom 48 m^2	25	6	4.36	5	0.57	4.48	5.10	0.019
Teachers' room 62 m^2	25	4	2.94	5	0.57	3.02	3.64	0.013
Meeting room 30 m^2	10	2	3.06	19	0.76	4.24	4.86	0.067
Meeting room 53 m^2	24	2	3.90	19	0.76	4.39	5.01	0.031
Cafeteria 18 m^2	8	0.5	3.76	15	0.71	5.21	5.83	0.013
Restaurant 260 m^2	154	1	4.85	15	0.71	6.03	6.65	0.002
Dressing room 18 m^2	25	0.25	10.3	19	0.76	12.7	13.4	0.004

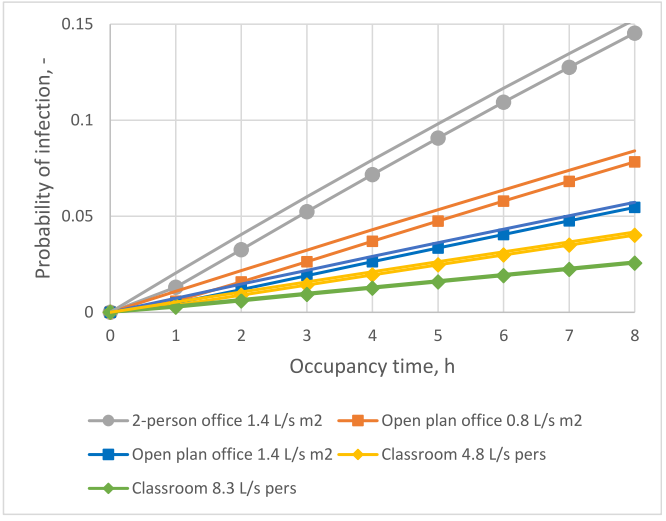


Fig. 3. Probability of infection in some rooms at 5 quanta/h and ventilation rates as reported in Table 4. Category III ventilation rates are calculated additionally for an open plan office and classroom. Solid lines without markers show the effect of steady state approximation, while lines with markers represent a dynamic concentration build-up.

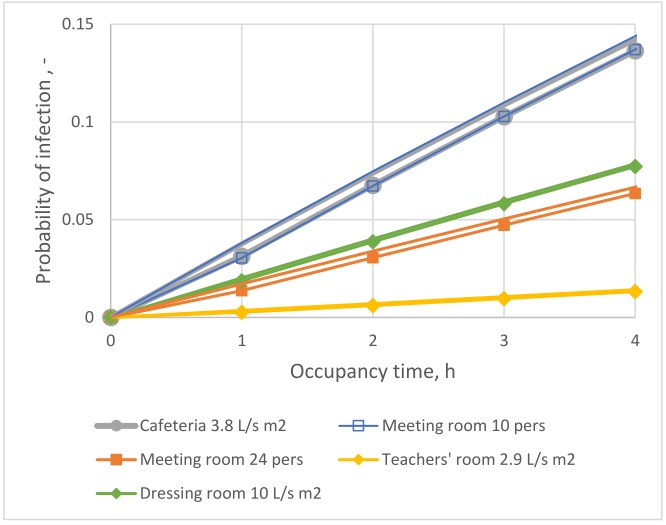


Fig. 4. Probability of infection in rooms with shorter occupancy time, ventilation rates and other input data as reported in Table 4. Solid lines without markers show the effect of steady state approximation, while lines with markers represent a dynamic concentration build-up.

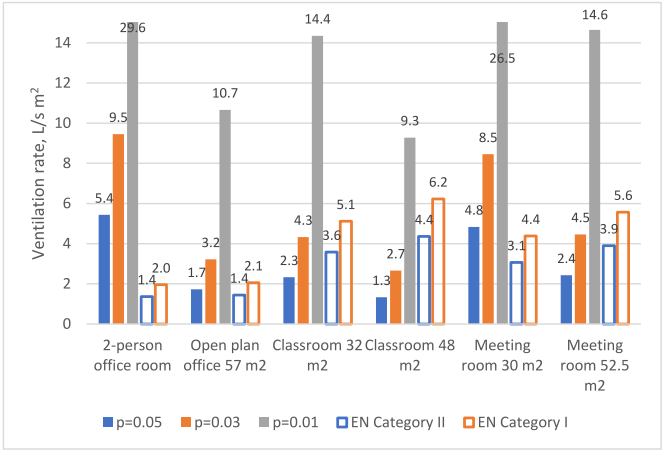
the large classroom. At the same time, a Category I ventilation rate is not enough for 1% probability in the smaller meeting room and in the open plan office. In the 2-person office, Category I ventilation is only enough for 5% probability.

To demonstrate that a lower individual probability of susceptible persons in large rooms may be a misleading indicator, because there are also more susceptible persons in large rooms which can lead to higher population level probability and bigger number of new disease cases, an acceptable individual probability values were calculated for the same rooms with equation (13) for $R = 0.5$. The maximum individual probability value was limited to $p = 0.1$ and the occupancy times reported in Table 3 were doubled for offices and classrooms (but not for meeting rooms) to describe a 2-day exposure that is attributed to asymptomatic persons. The required ventilation rates without masks are shown in Fig. 6. The results show that a high ventilation rate is required in the 2-person office and large classroom, but Category I ventilation is either enough or close to the required ventilation rate in other rooms. Because of the higher probability value in the case of a smaller number of persons, the required ventilation rate (per person and floor m^2) was smaller in the smaller classroom and meeting room compared with the larger rooms. The required ventilation rates correspond to about 80 L/s per infected person in an open plan office and a smaller meeting room (about 100 L/s in the 2-person office) and are higher in rooms with a higher number of occupants.

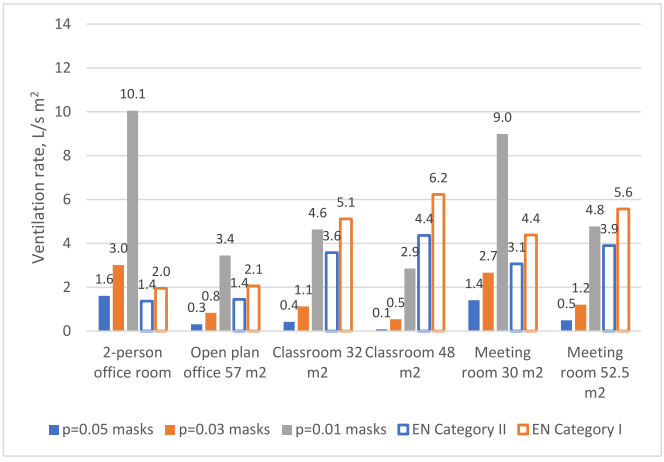
7. Limitations of the study

To develop new ventilation design method based on Wells-Riley model we have made the following assumptions:

- The model assumes that quanta are emitted at a constant rate throughout the event – for ventilation (capacity) sizing purposes we assume that infectious persons (typically one) are present and stay in the room throughout the event;
- Full mixing assumption means that the infectious respiratory aerosol quickly becomes evenly distributed throughout the well-mixed room



a)



b)

Fig. 5. Respiratory infection-based ventilation rates at three probability of infection levels compared with Category II and I ventilation rates for the case study rooms with sedentary activities with minor oral communication (5 quanta/h), a) without masks and b) with facial masks (mask filtration efficiency 0.5 for an infected person and 0.3 for susceptible persons).

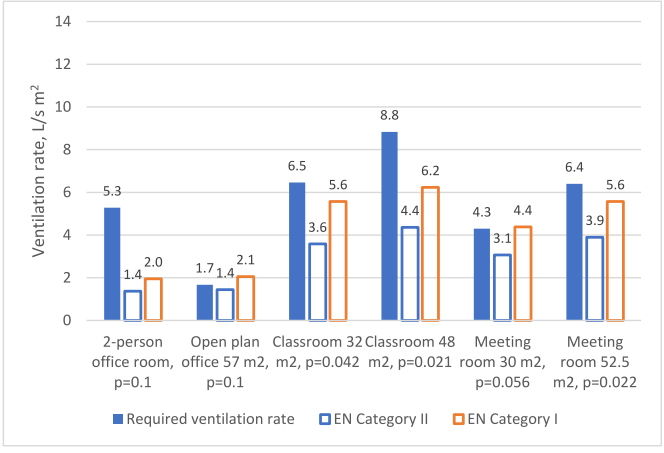


Fig. 6. Required ventilation rates without masks calculated with individual probability values corresponding to R = 0.5, but maximum probability limited to 0.1, with a 2-day occupancy. Occupancy times in offices and classrooms reported in Table 3 are doubled, but the same 2 h occupancy time is used for the meeting rooms.

air, however this assumption can be overcame by keeping physical distance of 1.5 m [25];

- Infectious quanta are removed by ventilation, filtration, deposition, and airborne virus decay;
- The model operates with individual probability of infection of susceptible persons for which acceptable values can be calculated from event reproduction number, however, defining acceptable risk levels for public indoor spaces and community risk assessment are out of the scope of the present work;
- Steady state assumption was applied in the design method which effects were evaluated in section 5 showing that the impact of slightly higher steady state concentration is on the safe side.

Two important uncertainties of the Wells-Riley present application are effects of quanta values and the full mixing assumption. The results are sensitive to quanta emission rates which can vary over a large range, as shown in Table 1. The uncertainty of these values is high. Increase in quanta emission rates will lead to slightly higher increase in ventilation rates required to keep the same probability. While quanta emission rates were increased by 30%, required ventilation rates increased by 33–50% and on average by 39% in the rooms studied. From the risk management perspective there are also superspreader events that are less frequent but may have higher emission rates as occurred in the choir case [7].

Full mixing assumption creates another uncertainty because, in large and high rooms, the virus concentration is not necessarily equal all over the room volume. Air distribution in rooms depends on many factors and it is not easy to give general recommendations in which rooms reasonable mixing can be expected. There is some evidence that this is the case in smaller rooms with volumes 100–300 m^3 [49]. Evidently the air distribution has to be designed to achieve mixing ventilation. For such cases it has been recommended that rooms up to 4 m high with a maximum volume of 300 m^3 could be reasonably well mixed [50]. Regarding the case study rooms, high uncertainties exist in the restaurant and large open plan offices, because of large floor area and volume. Addressing the concentration differences is out of the scope of this study, but in principle can be added to the design method through the ventilation effectiveness or dilution ratio as shown in Refs. [26,27]. To evaluate these parameters either CFD simulations or tracer gas measurements would be needed.

8. Discussion

In this study, a respiratory infection-based ventilation criterion was derived in the form of a new steady state ventilation model making it possible to calculate the required ventilation rate at a given probability of infection and quantum emission rate. This ventilation rate can be purely outdoor air or a sum of outdoor air and non-infectious outdoor air equivalent supplied by a room air cleaner. The model accounts also for other removal mechanisms and mask wearing.

The model was applied in case studies representing typical rooms in public buildings. It was shown that steady state approximation led to only a small overestimation (on the safe side) which corresponded to about a 30-min or shorter shift in the probability curve in rooms with Category II or I ventilation as defined by the standard EN 16798–1. The quanta emission rates used in this study represent estimates for SARS-CoV-2, but the concept may be applied to other airborne respiratory viruses with available quanta data.

The derived ventilation equation can be applied in standards to complement the existing ventilation criteria based on perceived air quality, emissions from building materials and specific pollutants. A respiratory infection-based ventilation rate calculated with the new model provides ventilation rate per infectious person (a room with one infectious person) hence is logically different compared with the common method of calculation of ventilation rates based on the number of occupants. The newly developed model can be applied to design rooms with a low infection risk, which as shown through present analyses can

be achieved with general ventilation. From the risk management perspective, ventilation rates especially in smaller rooms may become very high leading to ventilation systems clearly not feasible. An alternative solution is to use lower ventilation rates and to limit occupancy of such rooms to one person in epidemic conditions or use air cleaners. Together with ventilation design, other measures such as partitioning and zoning of rooms may be effective, so instead of one single solution there is rather a set of engineering measures to be combined in every case in most effective fashion.

To reduce the probability of infection, the parameter that matters is the total flow rate per infected person but the room volume also has a positive effect through deposition and deactivation removal mechanisms and slower concentration build-up. The probability of infection in the presented case studies was the lowest in large well-ventilated rooms. The probability of infection of $p = 0.05$ was achievable in most of rooms with Category I ventilation, as defined by EN 16798–1; this is the highest recommended ventilation in existing standards. The use of facial masks with conservative efficiency resulted in the risk of 1% with the Category I ventilation in both classrooms and the large meeting room, but in the small meeting room, the smaller open plan office and the 2-person office higher ventilation rates than recommended in the standard were needed.

If an acceptable level of individual probability of infection was selected to correspond to the event reproduction number of 0.5, the probability value depended on the number of persons ranging in the case studies from 0.02 to 0.06 and was limited in rooms with less than 6 persons to 0.1. Event reproduction number-based probability criterion changed the results so that in the smaller classroom and meeting room less ventilation (per person and floor m^2) was needed than in the larger classroom and meeting room. Category I ventilation was enough or close to the required level of ventilation in all rooms except the 2-person office and larger classroom.

While infection risk-based ventilation may lead to high ventilation rates, the ventilation systems must be demand-controlled. Demand control and flexibility are necessary not only to control the risk, but also to address other requirements including the control of indoor air pollution originating from inside and outside sources and, importantly, to control energy use: higher ventilation means higher energy use; therefore, ventilation should be adequate to the demand, but not unnecessarily high. Energy consumption associated with control of the indoor environment is a critical concern, given that buildings consume over 36% of energy globally [24]. Much of this energy is expended on heating/cooling outdoor air as it is brought indoors to maintain indoor air quality and, in some cases, thermal comfort. Therefore, while building designs should optimise the indoor environment quality in terms of health and comfort, they should do that in an energy-efficient way in the context of local climate and outdoor air pollution.

Application of infection risk-based ventilation criteria is supported by experience from hospitals – the only environment to date where infection risk control and ventilation are applied together. Hospital ventilation rates, typically 6–12 air changes per hour (ACH), support the fact that high-capacity ventilation is capable of keeping aerosol concentrations at low levels [25]. In non-hospital buildings, there are evidently lower emission rates and smaller numbers of infected persons per floor area. Thus, lower ventilation rates could suffice, and existing Category I and Category II ventilation rates in the EN 16798-1 standard [20] provide one possible starting point for analysis. When considering typical sizing according to this standard, outdoor air ventilation rates result in default Indoor Climate Category II to 1.5–2 L/s per floor m2 (10–15 L/s per person) in offices and to about 4 L/s per floor m2 (8–10 L/s per person) in meeting rooms and classrooms. Therefore, depending on occupant density, air change rates vary significantly, but the higher end of 4 L/s per floor m2 in meeting rooms and classrooms, corresponding to 5 ACH, shows that there are spaces in public buildings where air change rates are similar to those in patient rooms with precautions against airborne risks.

9. Conclusions

COVID-19 pandemic has demonstrated a need to reconsider the objectives of ventilation in buildings indicating the need to include the removal of airborne pathogens. A respiratory infection-based outdoor air ventilation model (equation) developed in this study can be applied in standards to complement the existing ventilation criteria and design rooms with a low infection risk. The new ventilation equation allows calculating the required ventilation rate at a given probability of infection and quanta emission rate. This ventilation rate is expressed as the rate per infected person (or room with one infected person). This is different from the commonly calculated rates depending on the number of occupants.

To estimate a low-risk ventilation rate, the event reproduction number was used. Category I ventilation satisfied the required ventilation rates in many, but not all type of spaces. The smallest required ventilation rates were about 80 L/s in the 6-person open plan office and the 10-person meeting room and about 100 L/s in the 2-person office. In rooms with a higher number of occupants, the required ventilation rates were higher. The large variation in the calculated case studies made it impossible to provide a simple rule of thumb for required ventilation rates and demonstrated the need to apply the developed ventilation design method.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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